International Journal of Thermal Sciences 127 (2018) 1–6

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Numerical investigation of radiation transfer in packed bed of semitransparent coated spherical particles

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ARTICLE INFO

Keywords:
Radiative properties
Packed bed
Semitransparent coated sphere
Monte carlo method

ABSTRACT

A packed bed of multilayered spherical particles plays a very important role in several engineering applications, such as the thermal insulation material of polystyrene foam and solar absorber for thermal energy conversion. In this study, we investigate the transmission of diffused beam in a one-dimensional densely packed bed. Spherical particles with double-layer structure and same radius are distributed randomly in transparent host media. The semitransparent inner layer is coated with a semitransparent shell. The size parameter χ of these spheres is sufficiently large to simulate their interaction with radiation through a Monte Carlo ray-tracing technique based on the geometrical optics approximation. After verification of the code for radiative transfer in a single coated sphere, the effects of optical thickness, refractive index, thickness, and porosity on the transmission are examined in detail. Transmittance and reflectance are employed to describe the radiative properties of a packed bed filled with multilayered semitransparent spherical particles.

1. Introduction

Radiation heat transfer in a fixed bed packed with semitransparent coated spheres exists in various systems, which has been reviewed a lot in the works of Dombrovsky and Baillis [1] [2], such as TiO_2-coated fused-silica sphere beds for the treatment of polluted air and water [3] [4], solar energy storage systems [5] [6], and monitoring of particulate-matter pollution [7], etc. Therefore, the accurate description of radiative optical properties is the key of the optimization, design, and scaling up of packed bed of spheres coated with semitransparent shell.

The radiative heat transfer in the packed bed of spheres was entirely reviewed in Refs. [8–10]. According to the ratio of the clearance between particles to wavelength c/λ, and the ratio of the clearance between particles to particle size c/d, closely spaced particles distributed randomly in a container are considered in this study. In other words, the interference and multi-scattering effects are considered [11] [12]. For the spheres with size parameter $\chi = \pi d/\lambda$, which is sufficiently large, two approximations, named "multiphase approach" [13] and "homogeneous phase approach" [14], are frequently employed. However, the former approach is not accurate for packed beds of semitransparent spheres [14]. Therefore, the latter one is widely adopted, in which effective radiative properties, such as absorption coefficient, scattering albedo, and phase function, are obtained. Subsequently, the radiative transfer equation (RTE) could be solved by DOM, FVM, and several other widely used numerical methods [15]. The Monte Carlo ray-tracing method is frequently employed to compute the radiative properties of packed bed of large spheres (χ»1), which capture accurately the ray transmission in the packed bed of spheres, including dependent scattering effect between spheres and ray transmission effect in a single sphere [16]. It is widely used for computing the effective radiative properties of a packed bed of opaque spheres [17] or absorbing–scattering spheres [10] [18] in a transparent and absorbing host medium.

Although the stable and accurate algorithms based on electromagnetism theory for radiative characteristics of a single multilayered sphere was reported considerably since many years ago [19] [20], investigation on the transmission of a beam in a densely packed bed of multilayered spheres is still scarce [21]. In general, this type of packed bed is considered as a pseudo-homogeneous medium. Moreover, the optical properties are estimated from experiments, which are expensive and time consuming [22]. To the best of our knowledge, only Imoberdorf et al. [3] [4] considered the interaction between packed bed of photocatalytic TiO_2-coated spheres and photons. Their results reveal that the bed expansion exhibits a strong influence on the radiation distribution and efficiency of the reactor. However, they assume that the TiO_2 shell layer is sufficiently thick for absorbing all the radiation, without considering the influence of the ray transmission in the internal glass sphere.

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https://doi.org/10.1016/j.ijthermalsci.2017.12.021
Received 30 September 2017; Received in revised form 16 November 2017; Accepted 19 December 2017

Nomenclature

d	diameter of sphere, $d = 2r$; m
$dist$	transmission distance; m
k	absorptive index
L	thickness of packed bed; m
n, n_i, n_t	refractive index
$Nabso_{sphere}$	number of rays absorbed by a coated sphere
$Ntran_{sphere}$	number of rays without being attenuated by a coated sphere
$Nreflect_{bed}$	number of rays reflected by packed bed of coated spherical particles
$Ntran_{bed}$	number of rays transmitted through packed bed of coated spherical particles
N_{ray}	number of rays used by Monte Carlo method
r	radius of sphere; m
R	reflectance of packed bed, $R = \frac{\sum Nreflect_{bed}}{N_{ray}}$
$Rand_\rho$, $Rand_\kappa$	random number
T	transmittance of packed bed, $T = \frac{\sum Ntran_{bed}}{N_{ray}}$
v^{mc}	numerical value obtained by Monte Carlo method
v^{Mie}	numerical value obtained by Mie theory
x, y, z	Cartesian coordinates; m

Greek letters

α_λ	spectral absorption of coated sphere, $\alpha_\lambda = \frac{Nabso_{sphere}}{N_{ray}}$
ε	porosity
ε_λ	spectral emissivity of coated sphere
θ_i, θ_t	polar angles of incident radiation and refracted radiation relative to the normal of sphere, respectively; rad
κ	absorption coefficient; m^{-1}
λ	wavelength; m
$\rho(\theta_i, \theta_t)$	reflectivity
χ	size parameter, $\chi = 2\pi r/\lambda$

Subscripts

1 and 2	inner sphere and spherical shell
bed	packed bed
sphere	coated sphere

The primary objective of this study is to explore the radiative characteristics of a densely packed bed of absorbing spheres coated with semitransparent shell distributed randomly in a transparent host medium. The influence of the optical properties of the internal sphere and the shell, such as the absorption coefficient and the refractive index, is entirely examined. This paper is organized as follows. In Section 2, the Monte Carlo ray-tracing technique is briefly summarized, and the code is verified. Then, the reflection and transmission characteristics of radiative transfer, such as the reflectance and transmittance, are presented in Section 3. Finally, the concluding remarks are provided in Section 4.

2. Monte Carlo method for radiative heat transfer in packed bed

In this study, the Monte Carlo ray-tracing algorithm [15] with a total number of $N_{ray} = 10^6$ rays is employed for determining the ray transmission in the packed bed of coated spheres (shown in Fig. 1 and Fig. 2). The packed bed is generated based on a type of random packing algorithm from Ref. [18]. The diffused beam is incident uniformly on the top of the packed bed. It propagates in the transparent host medium until it intersects a coated sphere. The reflection and refraction at the interface should be considered when the refractive index of the shell is different from that of the environment (air) or the internal sphere. The reflectivity can be calculated by the Fresnel reflection equation:

$$\rho(\theta_i, \theta_t) = \frac{1}{2}\left\{\left[\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)}\right]^2 + \left[\frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)}\right]^2\right\} \quad (1)$$

in which θ_i and θ_t are polar angles of incident radiation and reflected radiation relative to the normal of sphere, respectively; θ_t is determined by the Snell's law, $\theta_t = \arcsin\left(\frac{n_i}{n_t}\sin\theta_i\right)$. Then, a random number $Rand_\rho$ is generated to determine whether the ray is reflected or refracted. In this study, all the interfaces are assumed to be sufficiently smooth so that the specular reflection is verified. If $Rand_\rho \le \rho(\theta_i, \theta_t)$, the ray will be reflected; otherwise, the ray will be refracted and continue to travel on. The traveled distance $dist$ in the shell or internal sphere can be related to absorption coefficient κ and to random number $Rand_\kappa$ as:

$$dist = -\ln(Rand_\kappa)/\kappa \quad (2)$$

The details of the above procedure are available in our previous study [10]. The Monte Carlo code simulating the ray transmission in a packed bed of semitransparent coated spheres is shown in Fig. 3. Each ray is traced until it is absorbed by the spheres, escaped from the top of the packed bed, or passed through the packed bed, and is denoted by $Nabso_{bed}$, $Nreflect_{bed}$, and $Ntran_{bed}$, respectively. The procedure is repeated until the number of rays reaches N_{ray}. Transmittance $T = \frac{\sum Ntran_{bed}}{N_{ray}}$ and reflectance $R = \frac{\sum Nreflect_{bed}}{N_{ray}}$ are defined to describe the radiative properties of the packed bed of coated spheres.

The extinction efficiency factor, scattering albedo, and spectral emissivity of a single sphere were calculated and compared with the works of Coquard [23] and Dombrovsky [24] in our previous study [10]. Moreover, the transmission of diffused beam through packed beds of specularly reflecting opaque spheres or absorbing spheres in the transparent host medium are performed. All the results are in good agreement with those presented in previous studies. Therefore, in this paper, we present only the verification of the radiative characteristics of a single coated sphere. Based on Kirchhoff's law, for an isothermal coated sphere, the spectral emissivity ε_λ equals to the spectral absorption α_λ, which can be defined as $\alpha_\lambda = \frac{Nabso_{sphere}}{N_{ray}}$. The relative error is defined as follows to perform comparisons with the BHCOAT code [25], which is based on Mie theory.

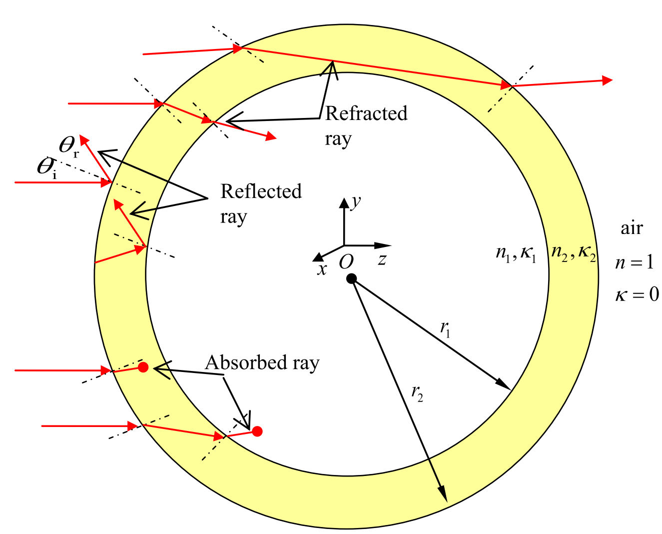

Fig. 1. Possible interaction events between incident beam and a two-layer semitransparent sphere.